A MODIFIED DIFFERENTIAL PICKUP REFLECTION PROBE

Sarit Sharma, Lalita Udpa, Yushi Sun and Satish Udpa

Department of Electrical and Computer Engineering
Iowa State University
Ames, Iowa 50011

INTRODUCTION

In the eddy current inspection of multi-layered structures in aircrafts, the detection of flaws in the subsurface layers is a significant challenge and requires very sensitive probes. These flaws are often present in the vicinity of edges of the structures and hence the inspection probe should also be capable of discriminating the defect signal from the edge signal. Edges in samples under inspection give rise to very large eddy current signals thereby masking any signals that the probe may detect from a flaw close to the edge. This is referred to as the edge effect. differential flux signal on inside and outside of the driver coil. A thin ferromagnetic shield around the probe coil is included to enhance the sensitivity of this probe.

A numerical model based on finite element analysis is used to study the probe performance and the associated magnetic flux distribution. Figure 1 shows the plot of magnetic flux linking a simple circular current carrying coil. It is observed that the flux spreads into an area that is much larger than the physical size of the coil. The area over

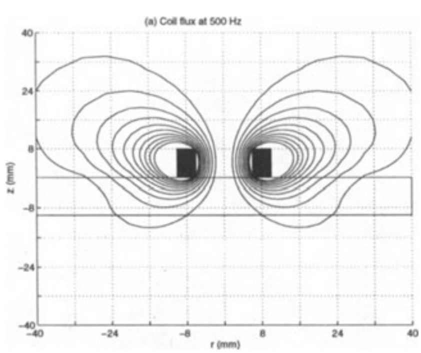

Fig. 1. Flux of a simple circular current carrying coil placed on a aluminum sample.

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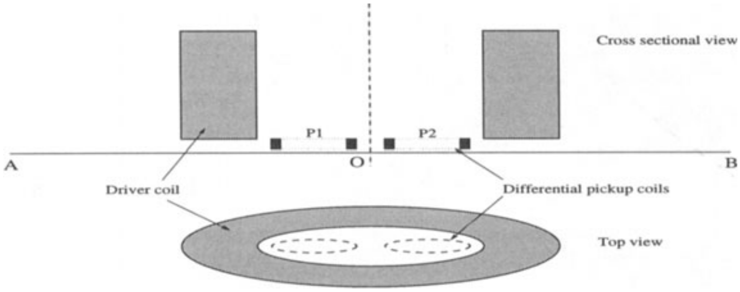


Fig. 2. The differential pickup reflection probe geometry for low frequency operation.

which the probe can sense a defect is defined by the area of the flux contours linking the coil which is often referred to as the probe footprint. A direct consequence of a large footprint is that the edge effect will be significant and the probe therefore may not be able to detect defects in the vicinity of edges.

Secondly, the detection of flaws deeper inside the samples requires the use of low frequency probes which implies use of large diameter coils needed to induce the eddy currents. However as the diameter of the sensing coil is increased the sensitivity of the probe reduces. This suggests the use of reflection (driver-pickup) probes with large diameter driver coils to induce the currents and small diameter pickup coils to sense the flaws. One of the more sensitive reflection probes is the differential pickup probe. This probe consists of a single driver coil with two pickup coils placed inside the driver coil and connected in a differential mode as shown in Figure 2. This probe is operated at low frequencies, typically < 10KHz and is shown to offer good resolution. The probe however does suffer from significant edge effect. An alternate design for a differential pickup reflection probe with higher sensitivity and lower edge effect is developed in this paper and described in the next section.

NEW PROBE DESIGN

Figure 1 shows that the flux lines of a coil form closed loops bounded by the axis of symmetry of the coil on one side and spread to infinity on the other. The width of the coil footprint in Figure 2 is given by AB. The footprint width may be reduced by half to OB if

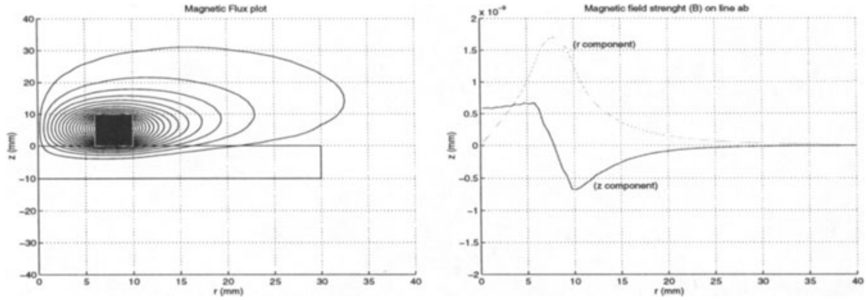


Fig. 3. The magnetic flux and magnetic field strength plots.

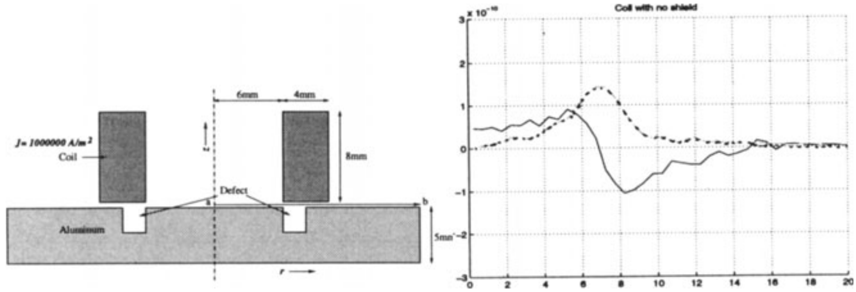


Fig. 4. $\Delta\vec{B}_z$ (dark line) and $\Delta\vec{B}_r$ (light line) as measured along the surface of the sample.

the pickup coils are placed so as to sense the flux in one half of the geometry inside the coil i.e. enclosed within OB. This is the rationale for the new probe design in which the probe is configured by moving the pickup coil $P1$ to outside of the driver coil between O and B. Numerical model simulations were used to obtain the optimal location of the pickup coils.

A test geometry including the probe coils on the top of an aluminum sample with a circular defect was modeled using the axissymmetric finite element analysis technique. Figure 3 shows the magnetic flux plot as well as the magnetic field strength in the sample surface (line OB in Figure 2) along the radial direction.

Using a two dimensional axisymmetric finite element model the signal predicted by the probe coil was measured. The signal measures the change in the magnetic field strength ($\vec{B}$) along the surface of the sample (line ab) caused by the presence of the defect. This change in the magnetic field strength $\vec{B}$ constitutes the defect signal.

Figure 4 shows the defect signal measured by the probe coil. The signal ($\Delta\vec{B}$) has two peaks similar to the $\vec{B}$ signal. The presence of a defect in the conducting sample causes a change in the flux linking the coil. Since the flux lines are closed loops enclosing the current source, any change in the flux inside also causes a change in the flux ouside the coil and two peaks in the defect signal are observed. This suggests the use of a differential measurement setup with one sensor of the differential pair measuring the positive peak and the other measuring the negative peak. Based on these model simulation results for the magnetic fields the new probe design was proposed.

Figure 5 shows the schematic of a probe that measures this differential flux signal.

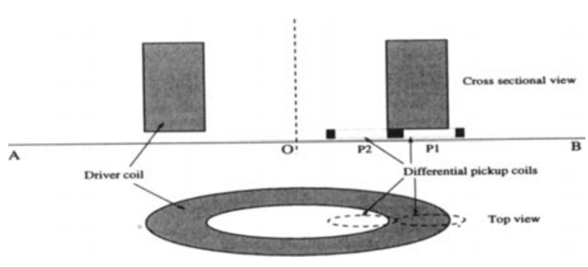


Fig. 5. Probe geometry for the differential pickup probe.

TABLE I

PARAMETERS OF THE NUMERICAL MODEL OF DIFFERENTIAL-PICKUP REFLECTION PROBE.

Parameter	Value
Driver coil radius r_d	9mm
Pickup coil radius r_p	4mm
Coil cross-section (driver and pickup)	2mm × 2mm
Coil current density J_s	10^6 A/m
Sample (Aluminum plate) size	100mm×100mm× 2mm
Defect size	4mm×2mm× 2mm (100%)
Frequency f	1 KHz
Conductivity σ_{Al} (Aluminum)	1.8868e+07 S/m
Permeability μ_r (Ferrite)	10000
Conductivity σ_{Fe} (Ferrite)	100 S/m

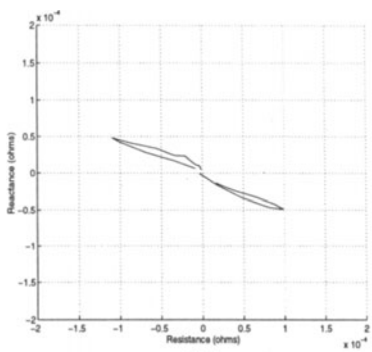
The probe consists of a driver coil and two pickup coils that are connected differentially. This probe will detect defects only in the direction in which the pickup coils are placed. In order to make the probe sensitive to defects in other directions multiple pairs of differential pickup coils can be placed along different locations on the circumference of the driver coil.

SIMULATION RESULTS

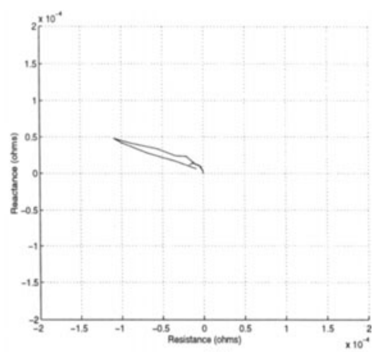
The finite element method (FEM) was used to simulate both the conventional and the new differential pickup probes. The governing equation for the underlying physical phenomenon is given by,

$$\nabla \times \frac{1}{\mu}(\nabla \times \vec{A}) = -j\omega\sigma\vec{A} + \vec{J}_s \quad (1)$$

where $\vec{A}$ is the magnetic vector potential, $\vec{J}$ the current density vector, μ and σ are the permeability and conductivity of the medium and ω is the angular frequency of the sinusoidal exciting current.



(a)



(b)

Fig. 6. Defect signals measured by the two pickup coils in (a) new and (b) conventional differential pickup reflection probe.

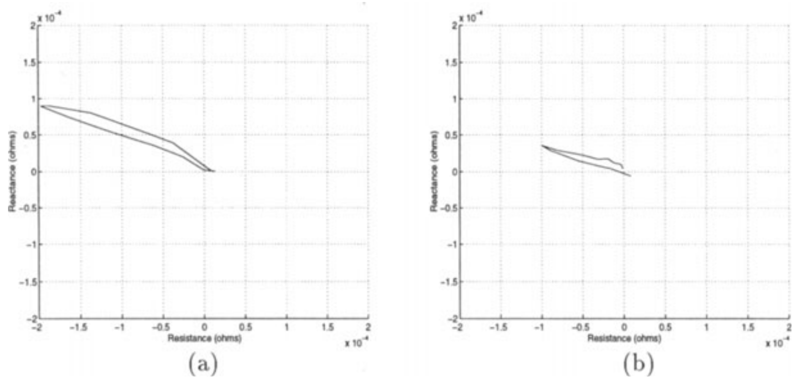


Fig. 7. Differential defect signals obtained by subtracting the two pickup coil signals for (a) new and (b) conventional differential pickup reflection probe.

The geometry shown in Figure 2 was modeled using the dimensions in Table I. A three dimensional (3D) finite element model was used to simulate the new designed probe. Table I gives the values of the parameters used in numerical model. The model consists of 6664 elements and 7875 nodes. The impedance Z of each of the pickup coils is computed using the equation

$$Z = -\frac{\partial \phi}{\partial t} = -j\omega\phi = -j\omega \int_S \vec{B} \cdot d\vec{S} \approx -j\omega \sum_{i \epsilon M} \vec{B}_i \cdot \vec{S}_i$$

where ϕ is the total flux enclosed by the coil, $\vec{B}$ the flux density, the $\vec{S}$ the surface area on the elements and M is the elements enclosed by the coil in a plane.

In the conventional probe the change in flux is sensed only in one of the pickup coils. In the new probe (Figure 5) we observe that any change in the flux linking one pickup coil will also cause a change in the flux linking the other pickup coil but in the opposite direction. The total defect signal as sensed by the pickup coils should therefore be approximately twice the magnitude sensed by the conventional probe.

Figures 6 (a) and (b) show the signals (change in impedance) measured by the new

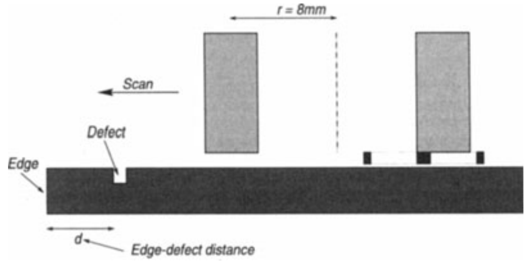


Fig. 8. Experimental setup to study the effect of edge on the new designed probe.

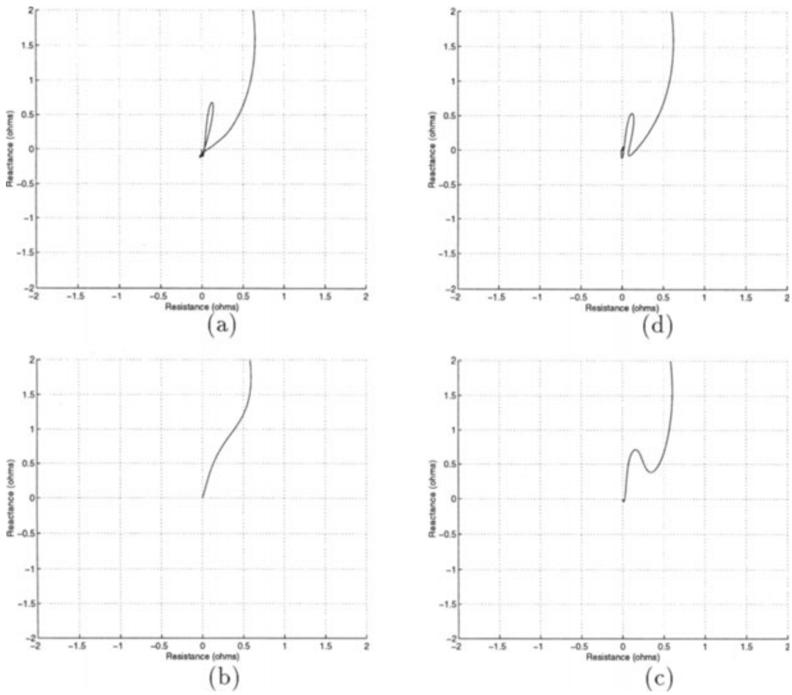


Fig. 9. Edge and defect signals for (a) d = 22mm, (b) d = 16mm, (c) d = 12mm and (d) d = 8mm.

and conventional differential-pickup reflection probes respectively as the probe scans the sample. In the finite element model the defect moves from the far field to the center of the driver coil i.e. from B to O in Figures 2 and 5. It is observed that the pickup coil $P2$ measures a negative signal in the new probe and almost zero signal in the old probe.

Figure 7 (a) and (b) show the differential signals (signal from $P1$ - signal from $P2$) measured by the new and conventional differential-pickup reflection probes respectively. The magnitude of the differential signal from the new probe is twice that from the old probe.

Figure 8 shows the experimental setup for studying the edge-effect as observed using the new designed probe. The setup consists of the sample plate with a defect at a distance d (the edge-to-defect distance) from the edge of the plate. The probe scans the sample towards the edge. The flux linking the pickup coils is not perturbed by the edge (or defect) until the edge (or defect) is past the axis of symmetry of the driver coil during the scan. The probe is therefore expected to be able to detect flaws for $d > r$.

Figure 9 shows the experimental signals obtained from the probe in the presence of a defect and an edge. The scan signals have been obtained for an edge-to-defect distance d of (a) 22mm, (b) 16mm, (c) 12mm and (d) 8mm. It is observed that the edge signal does not start to mask the defect signal for $d > 16mm(2r)$ whereas the expected result was that

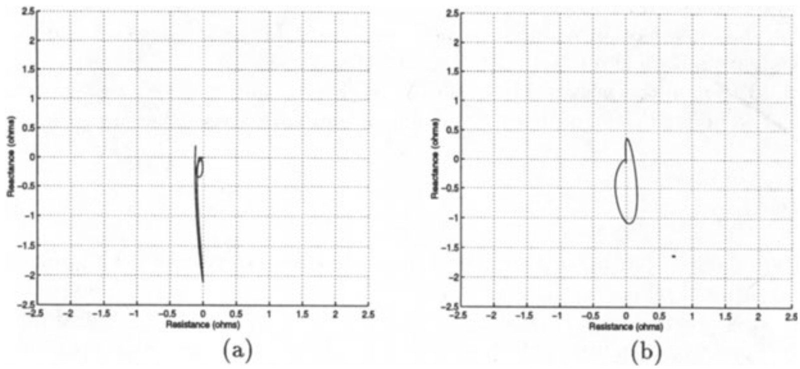


Fig. 10. Experimental signals for the (a) new designed and (b) conventional probes.

there will be no masking for $d > 8mm(r)$. Figure 10 shows the experimental signals obtained using the new designed probe and the conventional probe.

The numerical model has been further used to study the effect of ferromagnetic shielding on the eddy current defect signal. A ferromagnetic shield provides a low reluctance path for the magnetic flux and has the effect of concentrating the flux lines in a smaller area. The change in the field associated with the probe coil due to a defect in the sample is also concentrated in the same small area. The shield therefore seems to reduce the footprint and increase the probe sensitivity.

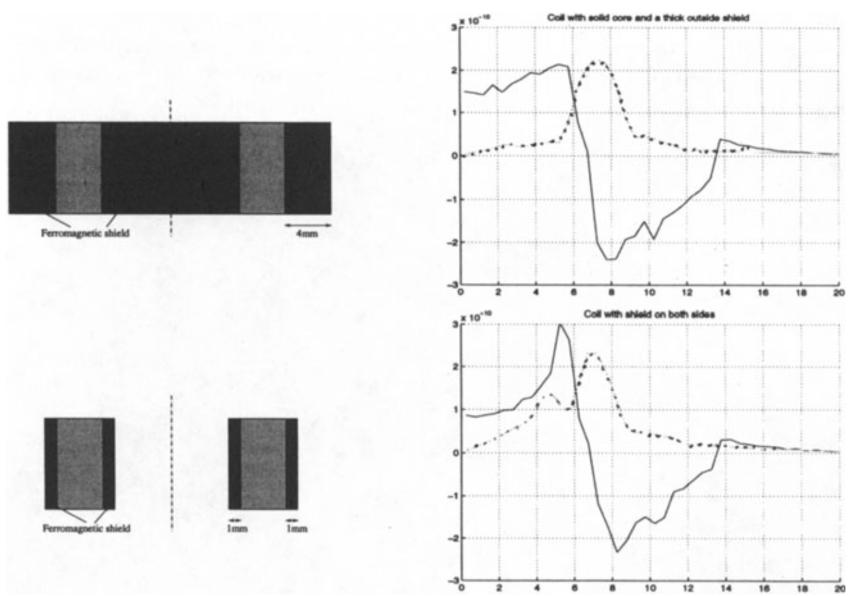


Fig. 11. $\Delta\vec{B}$ measured along the sample surface (continued) for different shield geometries.

Several different shielding configurations were studied and these results are presented in Figure 11. The effects of an inside core and outside shield thickness were studied, using the finite element numerical model. A thin shield of thickness 1mm and a ferromagnetic core were found to give the best result in the sense of maximum differential signal for a choosen defect. The results for the 1mm thin shield and core are as shown in Figure 11.

CONCLUSIONS

A new differential pickup coil reflection probe has been developed. The probe differs from the conventional reflection probe in the location of the pickup coils. The probe offers reduced edge effect and increased sensitivity relative to conventional differential pickup reflection probes. Extensive use of the two and three dimensional finite element model has been made in the design optimization studies.

ACKNOWLEDGEMENTS

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